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MAGNETIC MOMENTS OF 2^+ STATES IN EVEN Te NUCLEI

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The magnetic moments of the first 2^+ states in the even Te nuclei have been systematically investigated. The g_R values obtained increase from 0.44 for Te^{120} to 0.93 for Te^{128}. Not only are these values in strong disagreement with theory but the higher values are also substantially greater than Z/A.

Magnetic moments of first 2^+ states in even-even nuclei have been extensively studied in deformed nuclei where the states have low energies, $\lesssim 100$ keV, and relatively long lifetimes, $\lesssim 1$ nsec. The gyromagnetic ratios, $g_R = \mu/I$, are generally less than the hydrodynamic value, Z/A, and are in reasonably good agreement with the theory of Nilsson and Prior[1] in which pairing forces are taken into account. Away from the deformed region, where the 2^+ states have greater energy and shorter lifetimes, the experiments are commensurably more difficult and there are fewer data. Here the agreement with existing theory is poor.

In the present measurements the g_R values for the 2^+ states in Te are deduced from the measurement of the Larmor precession angle, $\omega_H\tau = -g\mu_N H\tau/\hbar$, of a gamma-ray angular distribution; the magnetic field used is the internal field at the nucleus of Te in the ferromagnetic environment of a metallic iron lattice. In deriving g_R from the measured $\omega_H\tau$, it is assumed that the effective magnetic field on Te, 611 kG, is that determined from Mössbauer studies[2] carried out on dilute alloys of Te in Fe at 4.2°K, corrected for the temperature dependence of the iron magnetization. The applied correction assumes room temperature, though some local heating from the incident oxygen beam would tend to increase the effective temperature, lowering the effective field.

The technique used for this study is that of Coulomb excitation in which the recoiling Te nuclei are impelled into a polarized iron foil. The method has been discussed in some detail in a previous publication[3] and is described briefly below.

A well collimated beam of 33-MeV oxygen ions from the University of Wisconsin tandem electrostatic accelerator strikes a target foil held between the pole pieces of a polarizing electromagnet. The target consists of an evaporated layer, 50 to 500 μg/cm^2 thick, of the isotope under study on an 8-mg/cm^2 iron backing. The backscattered oxygen ions are observed with an annular surface-barrier detector subtending center-of-mass angles of 175.9° to 161.7°. The energy spectrum of the backscattered ions allows easy separation of those scattered from the target and from the lighter host materials. Gamma rays emitted from Coulomb-excited nuclei, in coincidence with the selected backscattered O′, are detected in four coplanar 3-in. by 3-in. NaI(Tl) counter assemblies, rotatable from −135° to +135°, and are electronically routed into separate parts of the memory of a multichannel analyzer.

The $(\mathrm{O}'\gamma)$ angular distribution was determined with a Te^{122} on copper target. Copper is similar enough to iron to be a fair test of perturbations both during the slowing down process and after the ion has stopped in the lattice. As argued in Ref. 3, for the short lifetimes of concern here, little perturbation is expected; little if any was found. For the 0^p-2^γ-0 correlations studied,

$$W(\theta) = 1 + A_2P_2(\cos\theta) + A_4P_4(\cos\theta), \tag{1}$$

with

$$A_2 = (5/7)B_2^{\text{particle}}B_2^{\gamma},$$

$$A_4 = (-12/7)B_4^{\text{particle}}B_4^{\gamma},$$

and B_K^{i} are the known geometrical corrections. Experimentally, $A_2(\text{Cu}) = 0.60 \pm 0.02$ and $A_4(\text{Cu}) = -1.21 \pm 0.05$, compared with calculated values $A_2 = 0.65 \pm 0.06$ and $A_4 = -1.24 \pm 0.12$, the errors in the latter numbers arising from uncertainties in the B_K^{i}'s.

In the presence of a magnetic field perpendicular to the beam axis the angular distribution becomes[4]

$$W(\theta, \uparrow/\downarrow) = b_0 + \{b_2/[1+(2\omega_H\tau)^2]\}(\cos2\theta \mp 2\omega_H\tau\sin2\theta) + \{b_4/[1+(4\omega_H\tau)^2]\}(\cos4\theta \mp 4\omega_H\tau\sin4\theta), \tag{2}$$

where the arrows and the ∓ refer to field direction, up or down, and the b_n are well-known linear combinations of A_2 and A_4. The counters were placed near the points of greatest slope in the unperturbed angular correlation pattern, $\pm112\frac{1}{2}°$, $\pm67\frac{1}{2}°$, and $\pm22\frac{1}{2}°$, and the ratio $R(\theta)$ determined:

$$R(\theta) = \frac{W(\theta)\uparrow - W(\theta)\downarrow}{W(\theta)\uparrow + W(\theta)\downarrow} = -2\omega_H\tau\sin2\theta\left[\frac{b_2}{1+4(\omega_H\tau)^2} + \frac{4b_4\cos2\theta}{1+16(\omega_H\tau)^2}\right]\left(b_0 + \frac{b_2\cos2\theta}{1+4(\omega_H\tau)^2} + \frac{b_4\cos4\theta}{1+16(\omega_H\tau)^2}\right)^{-1}. \tag{3}$$

Figure 1 presents the $\omega_H\tau$ values obtained for each run and for each isotope as determined from Eq. (3). The experimental arrangement was the same, for all runs.

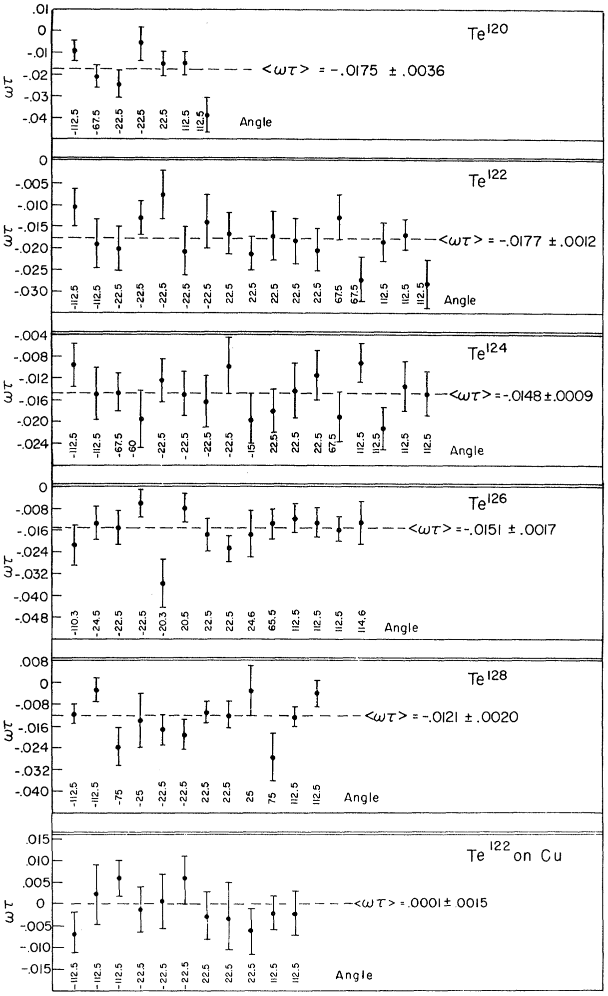
All of the targets were enriched to greater than 95% with the exception of Te^{120}, which was enriched to 45.5%. The principal contaminant, 12.3% Te^{122}, has a state at 564 keV which overlaps the 560-keV state of Te^{120}. The correction here was straightforward since $\omega_H\tau$ for Te^{122} was known.

Table I presents the $\omega_H\tau$ values obtained in these experiments and the extracted g_R values assuming an internal magnetic field of 611 ± 20 kG.[2] Included in the table are the energy values for the 2^+ excited states studied, the reduced electric quadrupole transition probabilities,[5] the lifetimes of the states,[5] and the predicted g_R values.[6] Also included in Table I are two recently reported radioactivity experiments on the 564-keV, $\tau = 11$ psec, state in Te^{122}. Both measurements use the 1250- to 564-keV, 2-2-0, γ-γ correlation from an Sb^{122} radioactive source imbedded in an iron lattice. Assuming the same τ and H_{eff} used here, the measured values are[7] $g_R = 0.39 \pm 0.06$ and[8] 0.44 ± 0.06 which are near Z/A and not significantly below the value $g_R = 0.54 \pm 0.04$. It should be noted that the angular correlation anisotropy, $[1/W(\theta)] \times dW(\theta)/d\theta$, for the γ-γ correlation, is 1/20 that observed with Coulomb excitation. For the small values of $\omega_H\tau$ of concern, the radioactivity measurements are therefore considerably more difficult than implantation measurements. There are, however, considerations with the implantation technique which do not arise with radioactivity measurements.

(1) The magnetic field on the incident and backscattered O ion could produce an effective turning of the angular distribution in the direction observed. The stray field is, however, too small to cause any appreciable effect. This point has been experimentally tested by measuring the effect of the magnetic field for the case of Te^{122} on Cu backing. In one of these runs an iron foil was placed behind the copper so that the magnetic geometry was identical with previous runs. No effect of the magnetic field was observed (Fig. 1), the value of $\omega_H\tau$ being

$$\omega_H\tau = 0.0001 \pm 0.0015.$$

(2) The effective lifetime is certainly different from the mean life of the state since some of the recoiling ions decay in flight. The stopping time for ~10-MeV Te in Fe was calculated, using the theory of Lindhard,[9] to be about 7×10^{-13} sec. No correction has been made for this effect since the number has large uncertainty. In any event, its effect is to increase the g_R



TELLURIUM DATA, ALL RUNS

FIG. 1. $\omega_H\tau$ values derived from the individual runs. The angles indicated are the angles of the NaI(Tl) detector with respect to the beam axis.

values still further (by ~20% for Te^{126} and Te^{128}), since H_{eff} is expected to be small for the moving atoms.

(3) The Te nuclei stop in indeterminate positions and the field need not be the same as observed with the metallurgically prepared samples used in the Mössbauer experiments[2] which yielded $H_{\mathrm{int}}(4.2°\mathrm{K}) = 620 \pm 20$ kG. There are several instances where internal fields have been investigated both with alloys and with the implantation technique. For Pt in Fe the fields are the same within the 10 to 20% errors involved.[10] For W in Fe the Mössbauer effect[11] yields 705 ± 25 kG, much higher than the 455 ± 30 kG observed with the implantation technique.[10,12] For Te^{122} in Fe, mentioned above, the values of H_{eff} are similar. Thus, there is no evidence for an enhancement of the internal field by the use of the implantation technique.

The effects discussed above either are negligible or serve to increase the g_R values above those shown in Table I. In order to lower the g_R values to near Z/A, the value of the effective magnetic field must be increased by at least a factor of 2 for the heavier isotopes. To do this would require a transient effect either as the Te atom and the crystal reach normalcy or as the Te ion is slowing down in the crystal. Such ad hoc explanations could account for g_R values which increase with decreasing lifetime of the 2^+ states in the heavier isotopes. There is no evidence for or against such conjectures.

The results for g_R are provocative for several reasons. The Te^{126} and Te^{128} g_R values are the largest yet reported by almost a factor of 2. Moreover, they are much greater than the-

Table I. Summary of experimental data on magnetic moments of 2^+ states in even Te isotopes.

Isotope	E (keV)	$B(E2)$ (10^{-49} cm^4)	τ (10^{-12} sec)	$-\omega_H\tau$	g_R(exp)	g_R(theor)[g]
Te^{120}	560	5.5 ± 1.1[a]	13.4	0.0175 ± 0.0036	0.438 ± 0.092	0.20
Te^{122}	564	6.5 ± 0.6[b]	11.0	0.0177 ± 0.0012	0.541 ± 0.036	0.17
				0.0154 ± 0.0015	0.44 ± 0.06[e]	
				0.0132 ± 0.0013	0.368 ± 0.06[f]	
Te^{124}	603	6.0 ± 1.2[c]	8.5	0.0148 ± 0.0009	0.585 ± 0.035	0.16
Te^{126}	667	5.32 ± 0.37[d]	5.82	0.0151 ± 0.0025	0.872 ± 0.144	0.18
Te^{128}	743	4.12 ± 0.33[d]	4.36	0.0121 ± 0.0020	0.932 ± 0.146	0.21

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oretically predicted. The predicted values[6] are not substantially different from those based on $z/(z+n)$ where n and z are the valence particles outside the closed shell between 50 and 82. This disagreement is perhaps not too surprising since similar theoretical models have so far not explained the large static quadrupole moments of 2^+ states in this region.

The predicted values are far below the values of either the implantation or the radioactivity results. Other recent measurements on first 2^+ vibrational states support the conclusions that g_R values of middle-weight even nuclei are often greater than Z/A. For Fe^{56},[13] Ru^{100},[14] Ru^{102},[14] and Pd^{106},[15] the g_R values are 0.55, 0.55, 0.44, and 0.45, respectively. For these cases n-n and p-p pairing, as well as polarization effects, are expected to be important. Te has the additional feature that both neutrons and protons are in the same shell. It may be that n-p pairing effects contribute substantially to g_R.

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$K_1{}^0$-$K_2{}^0$ MASS DIFFERENCE AND POSSIBILITY OF A S-WAVE DI-PION RESONANCE ABOVE 500 MeV*

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Under the assumption that the sign and magnitude of $K_1{}^0$-$K_2{}^0$ mass difference is due to the contribution of the two-pion intermediate state in the self-energy dispersion integral, it is found that the $I=0$ S-wave pion-pion interaction is strong near the K mass. The possibility of a di-pion resonance above 500 MeV is suggested.

Recent experiments[1] indicate that $\Delta m = m(K_1{}^0) - m(K_2{}^0) = -0.5/\tau_1$, where τ_1 is $K_1{}^0$ lifetime. Because the mass difference Δm is due to weak interaction, it is of interest to investigate whether the sign and magnitude of Δm can be understood by taking into account only a few low-mass intermediate states in the self-energy dispersion integral. In this note we wish to point out that if the S-wave $I=0$ pion-pion interaction is attractive and strong in the energy region near the K mass, the sign and magnitude of Δm can simply be understood. We evaluate the self-energy integral of $K_1{}^0$ in terms of the pion-pion interaction and derive a simple relation to relate the S-wave $I=0$ pion-pion phase shift δ_0 and Δm. It is found that, to account for the observed value of Δm, δ_0 must be approximately equal to 45° at the pion-pion energy of K mass.